August 1993

DCIEM No. 93-47

AD-A277 522

EFFECTS OF HEAT ACCLIMATION ON HEAT-EXERCISE TOLERANCE IN UNTRAINED AND ENDURANCE-TRAINED MEN WEARING NBC PROTECTIVE CLOTHING

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EXECUTIVE SUMMARY

Protective clothing imposes significant physiological and psychological stresses on the human body and may limit work tolerance, especially in hot environments. The additional strain imposed by protective clothing arises mainly because it is difficult for sweat to diffuse through relatively impermeable fabrics. Heat acclimation is a commonly adopted tactic to improve tolerance times when individuals must work in the heat. Potential benefits include increased sweating, expanded plasma volume, a lower metabolic rate for a given combination of exercise and heat stress, and a lower resting body temperature that allows greater heat storage. However, it is unclear whether such responses develop and/or are helpful when wearing protective garments with limited vapour permeability. Therefore, the purposes of this study were (1) to examine the influence of heat acclimation on exercise tolerance in a hot environment when untrained subjects were wearing either normal light combat clothing or clothing offering protection against nuclear, biological and/or chemical (NBC) agents and (2) to investigate possible interactions of heat acclimation with endurance training when wearing the two types of clothing.

Nine untrained (UT) and six endurance-trained (ET) males underwent 6 days of heat acclimation [60 min of treadmill walking or running at 45-55% of maximal aerobic power ($\dot{V}O_{2max}$) in a climatic chamber that was maintained at 40 ± 0.5°C and 30 ± 1% rh]. Subjects were tested before and after acclimation wearing either standard combat clothing or NBC protective clothing. Test sessions involved treadmill walking at 4.8 km·h^{-1} and 2% grade for a maximum of 120 min.

In UT subjects, heat acclimation increased plasma volume (+8%), but $\dot{V}O_{2max}$ and heat-exercise tolerance time were unchanged. When wearing standard combat clothing, acclimation decreased average values of heart rate, rectal temperature (T_{re}), mean skin temperature ($\bar{T}_{sk}$), thermal discomfort, and metabolic heat production. When wearing NBC protective clothing, the only significant change was in T_{re}. Acclimation induced an increase of sweat secretion but no statistically significant increase of sweat evaporation in NBC protective clothing. In ET subjects, acclimation reduced thermal discomfort when wearing standard combat clothing, and T_{re} and $\bar{T}_{sk}$ when wearing NBC protective clothing. The results suggest that heat acclimation did little to improve exercise tolerance when wearing NBC protective clothing in hot environments, although it reduced thermoregulatory strain by lowering mean body temperature, irrespective of training status. Further, acclimation added little to the benefit of endurance training other than reducing psychological strain when wearing standard combat clothing in hot environments.

ABSTRACT

Responses were compared between nine untrained (UT) men and six men who had participated in 8 weeks of endurance training (ET). Both groups underwent 6 days of heat acclimation in a climatic chamber that was maintained at 40 ± 0.5°C and 30 ± 1% rh. Subjects were tested before and after acclimation wearing either standard military combat clothing or nuclear, biological and/or chemical (NBC) protective clothing. Test sessions involved treadmill walking at 4.8 $km \cdot h^{-1}$ and 2% grade for a maximum of 120 min. In UT subjects, heat acclimation increased plasma volume (+8 ± 2%), but $\dot{V}O_{2max}$ and heat-exercise tolerance time were unchanged. When wearing standard combat clothing, acclimation decreased average values of heart rate, rectal temperature (T_{re}), mean skin temperature ($\bar{T}_{sk}$), thermal discomfort, and metabolic heat production. When wearing NBC protective clothing, the only significant change was in T_{re}. Acclimation induced an increase of sweat secretion but no statistically significant increase of sweat evaporation in NBC protective clothing. In ET subjects, acclimation reduced thermal discomfort when wearing standard combat clothing, and T_{re} and $\bar{T}_{sk}$ when wearing NBC protective clothing. The results suggest that heat acclimation did little to improve exercise tolerance when wearing NBC protective clothing in hot environments, although it reduced thermoregulatory strain by lowering mean body temperature, irrespective of training status. Further, acclimation added little to the benefit resulting from participation in 8 weeks of endurance training other than reducing psychological strain when wearing standard combat clothing in hot environments.

INTRODUCTION

Protective clothing imposes significant physiological and psychological stresses on the human body and may limit work tolerance, depending on work rate, environment, and fabric properties (Duggan 1988; White et al. 1989, 1991). Possible solutions include: (1) improvements in clothing design (Reischl and Stransky 1980; McLellan et al. 1992) and/or the use of a cooling garment (Pandolf et al. 1987; Nunneley 1988; Vallerand et al. 1991) and/or (2) the enhancement of cardiovascular and thermoregulatory defence mechanisms by physical training and/or heat acclimation.

Our previous study (Aoyagi et al. 1993) suggested that endurance training improved work tolerance only minimally when the subject was wearing protective clothing in a hot environment (40°C, 30% rh). Although training induced an increase in sweat secretion, this did not evaporate due to the low vapour permeability of the clothing ensemble.

Heat acclimation is characterized not only by an increased sweat secretion (Harrison 1985; Taylor 1986), but also (at least in some types of exercise) by a lowered rate of metabolism at any given intensity of heat stress (Sawka et al. 1983; Young et al. 1985). The latter change might improve heat tolerance even if the evaporation of sweat was impeded by protective clothing. Heat tolerance might also be improved by a lowering of resting body temperature, thus allowing greater heat storage (Shvartz et al. 1973). Many trials of heat tolerance have employed rhythmic bench-stepping exercise, which requires considerable skill and is relatively difficult to regulate for power output (particularly in an exhausted subject; Sawka et al. 1983). It is less clear whether heat acclimation would reduce the energy cost of an unskilled submaximal task such as moderate speed treadmill walking. It is also unclear whether heat acclimation could add to any gains of heat-exercise tolerance realized by endurance training in individuals who were wearing protective clothing.

Therefore, the purposes of this study were (1) to compare the influence of heat acclimation on work tolerance when untrained subjects were wearing either normal light combat clothing or nuclear, biological and/or chemical (NBC) protective clothing and (2) to investigate possible interactions of heat acclimation with endurance training when wearing the two types of clothing.

METHODS

Subjects

Following approval from the Human Ethics Committees of the University of Toronto and the Defence and Civil Institute of Environmental Medicine, nine untrained (UT) and six endurance-trained (ET) males served as volunteer subjects (Table 1). The ET subjects had previously completed an 8-week conditioning program [four 45-min running sessions per week at 80% of maximal aerobic power ($\dot{V}O_{2max}$) and an ambient temperature < 25°C, with a 17 ± 3% (mean ± SEM) increase of $\dot{V}O_{2max}$].

Testing was conducted from November through March, to avoid prior heat acclimatization. The $\dot{V}O_{2max}$ and maximal heart rate (HR_{max}) were determined (Aoyagi et al. 1993) both before and after 6 days of heat acclimation.

Heat-exercise tolerance test

Subjects exercised on a motor-driven treadmill (4.8 $km \cdot h^{-1}$, 2% grade) in a climatic chamber maintained at a temperature of 40 ± 0.5°C and a relative humidity (rh) of 30 ± 1%. Two types of clothing were worn in random order, with a minimum of 48 h separating test sessions: (1) standard combat clothing [underwear, socks, combat shirt and trousers, and leather boots; total weight = 4.4 kg; insulation = 0.217 $m^2 \cdot K \cdot W^{-1}$ (1.4 clo); permeability index = 0.44; and pumping coefficient = 0.25] or (2) NBC protective clothing [underwear, socks, combat shirt and trousers, NBC overgarment, NBC rubber gloves, leather and rubber boots, and respirator; total weight = 8.2 kg; insulation = 0.388 $m^2 \cdot K \cdot W^{-1}$ (2.5 clo); permeability index = 0.19; and pumping coefficient = 0.08]. Each subject completed 4 trials, wearing each of two clothing ensembles before and after heat acclimation.

Testing sessions lasted for a maximum of 120 min, criteria for halting a test being (1) a rectal temperature (T_{re}) of 39.3°C, (2) a maintained heart rate (HR) ≥ 95% of the subject's previously observed maximum for 3 min, or (3) unwillingness of the subject to continue the experiment.

Temperature measurements

A computerized data acquisition system (Hewlett-Packard 3497A control unit, 236-9000 computer, and 2934A printer) processed data from rectal and skin temperature sensors recorded at one minute intervals. Rectal temperature (T_{re}) was measured using a flexible vinyl-covered probe (Pharmaseal APC 400 Series) inserted approximately 12 cm above the anal sphincter. Local skin temperatures were measured at 12 sites, using uncovered copper-constantan thermistors (Yellow Springs Instruments thermistor bead 44004). The mean skin temperature ($\overline{T}_{sk}$) was calculated from weighted individual temperatures (Vallerand et al. 1989). Initial and final mean body temperatures ($\overline{T}_b$) during the heat-exercise tolerance test were estimated from T_{re} and $\overline{T}_{sk}$, using equations applicable to thermally neutral ($0.66T_{re} + 0.34\overline{T}_{sk}$) and hot ($0.79T_{re} + 0.21\overline{T}_{sk}$) environments, respectively (Colin et al. 1971).

Heart rate (HR) measurements

HR was monitored utilizing a telemetry unit (Sport Tester) clipped to an elasticized electrode belt that was fitted around the chest. The receiver, taped to the outside of the clothing, provided a continuous display of HR (5 s average) throughout each trial. HR values were recorded every 5 min.

Subjective measurements

Two subjective ratings were completed by the subjects every 10 min throughout the treadmill walking: (1) rating of perceived exertion (revised RPE scale; Borg 1982) and (2) rating of thermal discomfort (McGinnis RTD scale; Hollies 1977).

Respiratory gas exchange measurements

Open-circuit spirometry was used to determine expired minute ventilation ($\dot{V}_E$), oxygen consumption ($\dot{V}O_2$), and carbon dioxide output ($\dot{V}CO_2$) during submaximal exercise. An adaptor attached to a low-resistance Hans-Rudolf respiratory valve (for standard combat clothing) or the respirator (for NBC protective clothing) collected

expired air at minutes 13-15, 28-30, 43-45, and 58-60 of each hour. Expired gases were directed into a 5-L mixing box and then through an Alpha Technologies VMM 110 Series ventilation module for the determination of $\dot{V}_E$. A sampling line passed dried expired gases to Ametek S-3A O_2 and CD-3A CO_2 analyzers. The ventilation meter was calibrated with a syringe of 2 L volume and the gas analyzers were calibrated using precision-analyzed gas. After analogue-to-digital conversion (Hewlett-Packard 59313A A/D converter), $\dot{V}_E$, $\dot{V}O_2$, $\dot{V}CO_2$, and respiratory quotient (RQ) were calculated and printed on-line every 60 s, using a Hewlett-Packard 9825A microcomputer.

Weight measurements

Subjects were weighed nude (but fitted with the rectal temperature thermistor and connecting cable) and when dressed (also fitted with the rectal probe) before and after heat exposure. The electronic scale (Electroscale Model 921) was sensitive to the nearest 0.01 kg. Assuming that the contribution of insensible perspiration to the weight loss was similar ($0.02\ kg \cdot h^{-1}$; McArdle et al. 1991) for all subjects, the losses due to respiratory evaporation (m_e) and CO_2-O_2 exchange (m_r) were estimated using the equations of Mitchell et al. (1972) and Snellen (1966), respectively. Values for m_e and m_r were subtracted from the nude and dressed weight losses to give sweat production (SP, the sum of sweat evaporated plus sweat still soaking the clothing) and a weight loss due to sweat evaporation (SE) alone. Evaporative efficiency (EE) was calculated as $[(SE \cdot SP^{-1}) \cdot 100]$.

Heat balance analysis

A first estimate of heat storage (S_1) was calculated by the equation of Burton (1935):

$$S_1 = 3.47 \cdot BM \cdot (\Delta\overline{T}_b \cdot \Delta t^{-1}) \cdot A_D^{-1} \qquad \text{(Eq. 1)}$$

where 3.47 is the average specific heat of the body tissues ($kJ \cdot kg^{-1} \cdot {}^{\circ}C^{-1}$); BM is the body mass (kg); $\Delta\overline{T}_b \cdot \Delta t^{-1}$ is the rate of change in mean body temperature (${}^{\circ}C \cdot h^{-1}$); and A_D is the DuBois estimate of body surface area (m^2; Dubois and Dubois 1916).

An alternative estimate (S_2) was derived from the heat balance equation (Aoyagi et al. 1993; all units are in $kJ \cdot m^{-2} \cdot h^{-1}$). Metabolic rate (M) was determined by the equation of Gagge and Nishi (1983), using measured $\dot{V}O_2$ and RQ values. External power (W) was calculated from the treadmill speed and slope (Givoni and Goldman 1972). The latent (E_{res}) and dry (C_{res}) components of the respiratory heat exchange were calculated from the metabolic rate, according to the equation presented by Fanger (1970), allowing for the average temperature (38°C) and vapour pressure (49 Torr) in the upper respiratory tract. The latent heat loss from the skin surface (E_{sk}) was calculated from the rate of sweat evaporation ($kg \cdot h^{-1}$):

$$E_{sk} = 2425 \cdot SE \cdot A_D^{-1} \qquad \text{(Eq. 2)}$$

where 2425 is the energy equivalent of sweat evaporated ($kJ \cdot kg^{-1}$). The combination of dry heat gains by radiation and convection (R+C) was predicted by the following equation of Oohori et al. (1984):

$$R + C = (F_{cl} \cdot f_{cl} \cdot h) \cdot (\overline{T}_{sk} - T_a). \qquad \text{(Eq. 3)}$$

F_{cl} is Burton's thermal efficiency factor (non-dimensional), calculated as:

$$F_{cl} = (1 + 0.043 \cdot I_{clo} \cdot f_{cl} \cdot h)^{-1} \qquad \text{(Eq. 4)}$$

in which I_{clo} is the average thermal resistance of the clothing (CLO; 1 clo = 0.043 $m^2 \cdot h \cdot {}^\circ C \cdot kJ^{-1}$); f_{cl} is the ratio of the surface area of the clothing layer to the Dubois skin surface area (a value of approximately 1.2 for standard combat clothing and 1.4 for NBC protective clothing; Gagge and Nishi 1983); and h is the combined dry heat transfer coefficient (43.9 $kJ \cdot m^{-2} \cdot h^{-1} \cdot {}^\circ C^{-1}$) as described for the nude case by a combination of radiation (h_r, 17.7 $kJ \cdot m^{-2} \cdot h^{-1} \cdot {}^\circ C^{-1}$) and convection ($h_c$, 26.2 $kJ \cdot m^{-2} \cdot h^{-1} \cdot {}^\circ C^{-1}$). The linear values of h_r (Nishi 1981) and h_c (Nishi and Gagge 1970) can be approximated as:

$$h_r = 4 \cdot \sigma \cdot \varepsilon \cdot [(\overline{T}_{sk} + T_r) \cdot 2^{-1} + 273.15]^3 \cdot (A_r \cdot A_D^{-1}) \qquad \text{(Eq. 5)}$$

$$h_c = 23.4 \cdot V_{tw}^{0.39} \qquad \text{(Eq. 6)}$$

in which σ is the Stefan-Boltzmann constant ($20.4 \cdot 10^{-8}$

$kJ \cdot m^{-2} \cdot h^{-1} \cdot {}^{\circ}K^{-4}$); ε is the emissivity of the body (1); $\bar{T}_{sk}$ is the average observed mean skin temperature (36°C); T_r is the mean radiant temperature (40°C; T_r = the ambient temperature T_a, given an equal temperature of the chamber wall to the ambient environment); $A_r \cdot A_D^{-1}$ is the ratio of the effective radiating area of the body surface over its Dubois total surface area (a value of $0.72 \cdot A_D$ for A_r of a standing clothed person; Gonzalez 1988); and v_{tw} is the treadmill walking speed ($1.34\ m \cdot s^{-1}$).

Another variable, the dry heat exchange by conductance, was assumed to be negligible, given the small extent of contact between the garment and the skin surface and the minimal difference between the average observed temperatures of skin and clothing surface.

Blood measurements

Blood was sampled by finger prick. The hematocrit (Hct) was measured in duplicate, using a microhematocrit centrifuge. Hemoglobin (Hb) was determined in duplicate by spectrophotometry, cross-checked against the cyanmethemoglobin method, using Coulter 4C Plus cell control standards. Assuming no change of red cell packing with exercise or heat (Plyley et al. 1987), the percentage changes in blood volume (BV), red cell volume (CV), and plasma volume (PV) were calculated from values for Hb and Hct before and after heat acclimation, using the equations of Dill and Costill (1974).

Heat acclimation procedure

Six successive days of heat acclimation followed the first two clothing trials. Subjects walked or ran for 60 $min \cdot day^{-1}$ on a motor-driven treadmill at a speed and elevation demanding 45-55% of $\dot{V}O_{2max}$ (4.8-8.0 $km \cdot h^{-1}$ and 0-8% grade, depending on the subject's aerobic fitness), under the same environmental conditions (40°C and 30% rh) used for the heat-exercise tolerance test. During the heat acclimation exposures, subjects wore jogging shorts and a T-shirt, and were allowed to drink water *ad libitum*.

Statistics

Data are presented as mean values and standard errors of the mean (SEM). Paired *t*-tests compared pre- and post-acclimation anthropometric, physiological, and subjective variables. Differences of sweat rate between pre- and post-acclimation were compared before and after covariance adjustment for the confounding variables T_{re} and $\bar{T}_{sk}$. The relationships between RPE and RTD for the two clothing ensembles were tested by linear correlation calculations, *including* all *data points* for *each* subject. A two-factor (subject [averaged over exposure] and treatment) repeated measures analysis of variance analyzed changes in cardiorespiratory and thermoregulatory measures for each type of clothing. When a significant *F* value was obtained for the time x treatment interaction (after adjustment for the repeated measures factor by the Greenhouse-Geisser method), the *post-hoc* Newman-Keuls multiple comparisons procedure was used to locate significant differences. All statistical contrasts were accepted at the 0.05 level of significance.

RESULTS

Subject characteristics

Paired *t*-tests revealed no significant changes in anthropometric variables over the 6 days of heat acclimation (Table 1). The $\dot{V}O_{2max}$ was also unchanged after heat acclimation (Table 1).

The UT group developed a significant decrease of hematocrit (Hct, -2%) and hemoglobin (Hb, -5%), resulting in a small but significant increase of estimated blood volume (+5%) and plasma volume (+8%), with little change of red cell volume (Table 2). On the other hand, the ET group showed no significant change in blood data.

Heat-exercise tolerance time (HETT)

Neither group showed any significant difference in HETT after heat acclimation (Table 3), although acclimation tended to increase

HETT (5 min; $p = 0.06$) in the ET group when they were wearing NBC protective clothing.

Respiratory gas exchange

Heat acclimation tended to decrease the mean gas exchange values (pooled over an entire session). These changes were statistically significant for $\dot{V}O_2$ and $\dot{V}CO_2$ in the UT group when wearing standard combat clothing and for $\dot{V}_E$ and RQ in the ET group when wearing NBC protective clothing (Table 4). The only adverse effect was that the UT group showed a significantly higher mean $\dot{V}_E$ when wearing NBC protective clothing after heat acclimation.

Heart rate

In the UT group, after heat acclimation the average rate of increase in HR during the standard combat clothing trial was significantly slower beyond 15 min of exposure (Figure 1), with a lower overall mean HR (about 13 beats$\cdot$min^{-1}). The HR during the NBC protective clothing trial was slightly slower after heat acclimation but only at 45 min, when the majority of subjects terminated the test. Heat acclimation had no significant effect on HR in the ET group, although there was a tendency toward a lower post-acclimation HR (around 6 beats$\cdot$min^{-1}) throughout the NBC protective clothing trial.

Rectal and skin temperatures

After acclimation, the UT group showed a significantly lower T_{re} (0.2-0.3°C) throughout both clothing trials (Figure 2). Heat acclimation had no significant effect on the T_{re} of the ET group when wearing standard combat clothing, but decreased the mean T_{re} and the rate of increase in T_{re} (significantly after 25 min) when wearing NBC protective clothing.

Heat acclimation decreased the overall mean skin temperature ($\overline{T}_{sk}$) by 0.1-0.3°C for all clothing trials (Figure 3). Statistically significant effects were noted in the UT group when wearing standard combat clothing and in the ET group when wearing

NBC protective clothing.

Relative work load and subjective ratings

When the UT group wore standard combat clothing, the relative work intensity (RWI, -3%) and thermal discomfort (RTD, -9%) were significantly lower after heat acclimation (Table 5). However, heat acclimation had no effect on their subjective ratings when wearing NBC protective clothing. The ET group made a significantly lower RTD (-4%) and tended to a lower rating of perceived exertion (RPE, -11%; $p = 0.05$) during the normal combat clothing trial that followed heat acclimation, but as with the UT subjects, their ratings were unaltered when wearing NBC protective clothing.

Among the UT group, correlation coefficients relating all data on RPE and RTD for all subjects were 0.84 ± 0.03 (pre-acclimation) and 0.79 ± 0.10 (post-acclimation) when wearing standard combat clothing and 0.92 ± 0.02 (pre) and 0.94 ± 0.02 (post) when wearing NBC protective clothing. Corresponding values for the ET group were 0.80 ± 0.08 (pre) and 0.86 ± 0.07 (post) when wearing standard combat clothing and 0.94 ± 0.03 (pre) and 0.92 ± 0.04 (post) when wearing NBC protective clothing.

Sweat data

In the UT group, heat acclimation did not change sweat production (SP) when wearing standard combat clothing (Table 6). It significantly increased SP (+12%) when wearing NBC protective clothing, but this did not lead to any increase in sweat evaporation (SE). The ET group showed non-significant trends to an increase of SP in both standard combat clothing (+7%) and NBC protective clothing (+7%), with no significant change of evaporative efficiency (EE). In all trials, the differences of mean SP between pre- and post-acclimation were increased (0.01-0.36 $kg \cdot h^{-1}$) after covariance adjustment for changes in central (T_{re}) and peripheral ($\overline{T}_{sk}$) sweating drives, although unfortunately the data were insufficient to test the linearity of these effects (Table 7).

Heat balance

After acclimation, the UT group showed significant decreases (-5%) in M, E_{res} and C_{res}, an increase in R+C (+6%), and non-significant tendencies toward decreased S_1 (-9%) and S_2 (-19%) when wearing standard combat clothing (Table 8). However, the same variables were unchanged when wearing NBC protective clothing. The ET group showed a significant decrease in S_2 (-48%) when wearing standard combat clothing and a decrease in S_1 (-6%) and an increase in R+C (+15%) when wearing NBC protective clothing.

DISCUSSION

The influence of the 6-day heat acclimation program upon heat-exercise tolerance varied, depending on the initial aerobic fitness of the subjects and the type of clothing worn. In untrained subjects, heat acclimation decreased all measures of cardiovascular (HR), thermoregulatory (T_{re} and $\bar{T}_{sk}$), and psychological stresses (RPE and RTD) when wearing standard combat clothing, but it was of limited benefit when wearing NBC protective clothing. In contrast, endurance-trained subjects gained little benefit when wearing standard combat clothing, but they showed some decreases of thermoregulatory stress when wearing NBC protective clothing.

In the untrained subjects, the interaction of plasma volume, sweat rate, and HR with heat acclimation was similar to that previously seen with endurance training (Aoyagi et al. 1993). An estimated 8% exercise- or acclimation-induced expansion of resting plasma volume probably made a major contribution to the reduction of cardiovascular strain when wearing standard combat clothing. In contrast, when wearing NBC protective clothing, any gains from expansion of plasma volume were apparently offset by the negative circulatory effects of a 12% increase in sweat rate. In the trained subjects, on the other hand, heat acclimation was apparently of greatest benefit.

Heat acclimation often involves a lowering of thermoregulatory "set point" (Werner 1980; Gisolfi and Wenger 1984; Wenger 1988), with a reduced resting temperature (Shvartz et al. 1973) and decreased thresholds for sweating (Nadel et al. 1974) and vasodilation (Roberts et al. 1977). In the present study, heat

acclimation decreased the resting T_{re} ($\approx 0.2^{\circ}C$), irrespective of the training status of the subjects. In theory, the lower initial T_{re} should increase heat-exercise tolerance time, even if the rate of increase in T_{re} was unchanged by heat acclimation. In fact, acclimation also slowed the rate of increase in T_{re} by $0.1-0.2^{\circ}C \cdot h^{-1}$. Thus, heat acclimation should have increased heat-exercise tolerance time by at least 10 min, but paradoxically, the expected increases were not seen. Goldman (1988) has pointed out that if more than 40% of the skin is wetted, this decreases both performance and exposure time, particularly if there is an easy option to discontinue a test, as in the present study. Therefore, the acclimation-induced increase in sweat secretion and the decrease in evaporative efficiency when wearing the NBC protective clothing actually increased the number of subjects terminating the exposure of their volition (from 2 to 4 men for the UT group and from 3 to 4 men for the ET group).

The sweat rate of the untrained subjects was unchanged when wearing standard combat clothing (although T_{re} was lower). The absence of any increase of sweating reflects the acclimation-induced decrease of mean body temperature, rather than any inhibition of sweat gland activity, associated with wetness of the skin and clothing (Taylor 1986; Sawka and Wenger 1988) or dehydration (Sawka 1988). In contrast, heat acclimation tended to increase the sweat rate of the trained subjects when wearing standard combat clothing. In such a humid microenvironment, heat acclimation may alter the distribution of sweating, increasing sweat production on the limbs and making sweating more uniform (Taylor 1986; Wenger 1988). This could cause additional evaporation from the clothing (≈ 0.04 $kg \cdot h^{-1}$), augmenting the discrepancy between our two estimates of heat storage (S_1 and S_2) or between pre- and post-acclimation S_2 when wearing standard combat clothing. In particular, the latter finding implies that effective cooling might be severely limited, if the wetted area of light and loose-fitting clothing was increased and the total sweat evaporation (including the quantity of sweat dripping from the body) was beyond approximately 0.60 $kg \cdot h^{-1}$.

The low permeability of the NBC protective clothing restricted evaporation of sweat. Nevertheless, the trained subjects showed a slight tendency to an increase in the total volume of sweat evaporated (≈ 0.02 $kg \cdot h^{-1}$) after heat acclimation. It may thus be worth examining whether more heat could be dissipated when wearing

NBC protective clothing, if a longer time were allowed for permeation and evaporation of the sweat secreted and/or sweat secretion were increased up to the limit of possible sweat evaporation. However, adoption of such a tactic would depend on the availability of sufficient water to avoid dehydration (Goldman 1988; Maughan and Noakes 1991).

The rate of increase in core temperature for a lightly clothed person is proportional to the heat produced by metabolism (Nielsen 1969; Stolwijk and Nadel 1973), irrespective of the type of exercise that is performed (for example, positive vs. negative work or arm vs. leg work). Some investigators have reported that heat acclimation decreases the rate of metabolism elicited by submaximal exercise (Sawka et al. 1983; Young et al. 1985), but other authors have disputed this claim (King et al. 1985; Kirwan et al. 1987). In the present study, acclimation apparently induced a small (< 5%) reduction in metabolic rate, more marked with standard combat clothing than with NBC protective clothing. Sawka et al. (1983) postulated the following mechanisms for a reduced energy expenditure after heat acclimation: (1) reduced cardiovascular stress, (2) learning of and habituation to the test exercise, (3) a Q_{10} effect, (4) an improved muscular efficiency caused by local gains in contractile-coupling efficiency rather than a change in phosphorylation efficiency, and (5) a greater recruitment of slow-twitch motor units, related to increased proprioceptive afferent activity. However, they rejected all hypotheses except for the fifth. To their list must be added (6) improved coordination in a subject who is less distressed and (7) (in vigorous exercise) a decreased percentage contribution of anaerobic (or perhaps more precisely, glycolytic) metabolism, associated with an increased perfusion of active skeletal muscles.

Our previous study (Aoyagi et al. 1993) suggested that endurance training led to decrements of exercise HR, but there was little resultant change in metabolic cost, whether wearing standard combat clothing or NBC protective clothing (rejecting *Hypothesis 1*). The extent to which heat acclimation can reduce the metabolic rate depends on the exercise mode and the test environment. In general, a larger decrease of energy cost is seen when performing a skilled task at a high ambient temperature (see Table 1 in Sawka et al. 1983). Our heat acclimation program reduced the energy cost of treadmill walking, although this task requires little skill (rejecting *Hypothesis 2* and possibly *6*). According to the law of

van't Hoff, the rate of many biologic reactions roughly doubles with a 10°C rise in temperature (Murray et al. 1988). Thus, the small reduction (0.2-0.3°C) of T_{re} and $\bar{T}_{sk}$ might contribute to the decreased metabolic rate after heat acclimation (accepting *Hypothesis 3*). Any dependence on anaerobic metabolism is greater in the heat than in cooler conditions (possibly due to the redistribution of blood flow away from the exercising muscles or the increased recruitment of fast-twitch motor units; Dimri et al. 1980; Sawka and Wenger 1988; Young 1990). A glycogen sparing effect of acclimation has previously been observed during exercise in the heat (King et al. 1985; Kirwan et al. 1987; Young 1990). However, our subjects were exercising at a relatively low intensity, and respiratory gas exchange measurements show no consistent relationship with the reduced metabolic cost. This suggests that there was little alteration of metabolic pathways or motor unit recruitment patterns after heat acclimation (rejecting *Hypothesis 5* and *7*). Acclimation led to some reduction of average RQ in the trained subjects when wearing NBC protective clothing, but this may be attributed to a lessening of hyperventilation (which is commonplace when respirators and fullface masks are first worn, particularly in hot-wet environments; Morgan 1983; Goldman 1985; Knochel 1989). The evaluation of *Hypothesis 4* is beyond the scope of the present study. Young (1990) has speculated that a mitochondrial adaptation to chronic heat stress enables mitochondrial phosphorylation efficiency to be maintained as muscle temperature rises.

Heat acclimation did not change the $\dot{V}O_{2max}$ and thus the relative intensity of the treadmill exercise (although it may have helped to conserve the effects of training in the trained subjects). However, there was a tendency toward a decrease of perceived exertion (RPE), in both untrained and trained subjects when wearing standard combat clothing. Given the close correlation of RPE and RTD, this trend may reflect a significant decrease in the thermal strain (RTD). In contrast, acclimation had no beneficial effect on subjective ratings when wearing NBC protective clothing. This probably reflects an offsetting discomfort associated with an accumulation of sweat within the garment.

CONCLUSIONS

The effects of heat acclimation on physical performance in the heat have some similarities to those seen after endurance training, whether the subjects are wearing normal or protective clothing. Heat acclimation also lowers the thermoregulatory "set point" and reduces the energy cost of a given task, thus adding to the benefits of endurance training, but it does not necessarily improve exercise tolerance in the heat, especially when sweat accumulates within NBC protective clothing.

ACKNOWLEDGEMENTS

This research was supported by a Department of National Defence research contract. The authors gratefully acknowledge the technical assistance of Mr. J. Pope, R. Limmer, and Mrs. D. Kerrigan-Brown throughout the study. We would also like to thank the subjects for their participation in this investigation.

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Table 1. Physical characteristics and maximal aerobic power ($\dot{V}O_{2max}$) of untrained (UT) subjects and subjects participating in endurance training (ET) before and after heat acclimation

Group	Condition	Age (yr)	Height (cm)	Body Mass (kg)	A_D (m^2)	$\dot{V}O_{2max}$ ($mL \cdot kg^{-1} \cdot min^{-1}$)
UT	Pre-acclimation	25±1	176±2	83.6±3.8	2.00±0.05	43.9±1.7
	Post-acclimation	25±1	176±2	83.1±3.5	1.99±0.05	45.7±2.1
ET	Pre-acclimation	31±1	177±2	78.9±4.6	1.95±0.04	47.4±2.4
	Post-acclimation	31±1	177±2	78.7±5.0	1.95±0.05	46.0±1.9

Values are means ± SEM. n = 9 for the UT group and n = 6 for the ET group. A_D, DuBois body surface area.

Table 2. Observations on the blood of untrained (UT) subjects and subjects participating in endurance training (ET) before and after heat acclimation

Group	Condition	Hct (%)	Hb ($g \cdot 100\ mL^{-1}$)	ΔBV (%)	ΔPV (%)	ΔCV (%)
UT	Pre-acclimation	49.0±0.7	17.3±0.3			
	Post-acclimation	47.3±0.8*	16.5±0.3*	4.7±1.7*	8.4±2.3*	1.0±1.3
ET	Pre-acclimation	46.2±0.7	16.2±0.2			
	Post-acclimation	45.8±0.8	16.1±0.2	0.6±1.2	1.2±1.2	-0.3±1.7

Values are means ± SEM. n = 9 for the UT group and n = 6 for the ET group. Hct, hematocrit; Hb, hemoglobin; ΔBV, blood volume changes; ΔPV, plasma volume changes; and ΔCV, red cell volume changes.
*, significantly different from pre-acclimation value by paired *t* test ($p < 0.05$).

Table 3. Heat-exercise tolerance time (HETT) and reasons for test termination. Untrained (UT) subjects and subjects participating in endurance training (ET) wearing standard combat clothing and NBC protective clothing before and after heat acclimation

Group	Condition	Standard Combat Clothing					
		HETT		Reason for test termination			
		(min)		HR	RT	SD	TL
UT	Pre-acclimation	116±3	(92-120)	1	1	0	7
	Post-acclimation	118±2	(105-120)	0	0	1	8
ET	Pre-acclimation	120±0		0	0	0	6
	Post-acclimation	120±0		0	0	0	6

Group	Condition	NBC Protective Clothing					
		HETT		Reason for test termination			
		(min)		HR	RT	SD	TL
UT	Pre-acclimation	50±3	(39- 68)	5	2	2	0
	Post-acclimation	49±3	(32- 58)	3	2	4	0
ET	Pre-acclimation	47±2	(40- 56)	1	2	3	0
	Post-acclimation	52±3	(43- 60)	1	1	4	0

Values for "HETT" are means ± SEM, with range of observations in parentheses. Figures for "Reason for test termination" are the number of subjects. n = 9 for the UT group and n = 6 for the ET group. HR, heart rate (≥ 95% HR_{max} for 3 min); RT, rectal temperature (39.3°C); SD, subject's desire; and TL, time limit (120 min).

Table 4. Respiratory gas exchange measurements. Untrained (UT) subjects and subjects participating in endurance training (ET) wearing standard combat clothing and NBC protective clothing before and after heat acclimation

Group	Condition	Standard Combat Clothing			
		$\dot{V}_E$ ($L \cdot min^{-1}$)	$\dot{V}O_2$ ($L \cdot min^{-1}$)	$\dot{V}CO_2$ ($L \cdot min^{-1}$)	RQ
UT	Pre-acclimation	28.9±1.4	1.46±0.07	1.17±0.05	0.80±0.01
	Post-acclimation	28.2±1.2	1.38±0.05*	1.11±0.04*	0.80±0.01
ET	Pre-acclimation	29.7±1.7	1.37±0.06	1.18±0.04	0.86±0.01
	Post-acclimation	28.8±1.9	1.32±0.07	1.13±0.06	0.85±0.02

Group	Condition	NBC Protective Clothing			
		$\dot{V}_E$ ($L \cdot min^{-1}$)	$\dot{V}O_2$ ($L \cdot min^{-1}$)	$\dot{V}CO_2$ ($L \cdot min^{-1}$)	RQ
UT	Pre-acclimation	33.0±2.2	1.54±0.09	1.32±0.07	0.86±0.01
	Post-acclimation	35.8±2.0*	1.56±0.07	1.33±0.06	0.85±0.01
ET	Pre-acclimation	39.0±2.7	1.58±0.08	1.44±0.08	0.91±0.02
	Post-acclimation	35.3±1.8*	1.55±0.07	1.37±0.07	0.88±0.01*

Values are means ± SEM, observed during 90-120 min in standard combat clothing and 30-45 min in NBC protective clothing. n = 9 for the UT group and n = 6 for the ET group. $\dot{V}_E$, expired minute ventilation; $\dot{V}O_2$, oxygen consumption; $\dot{V}CO_2$, carbon dioxide production; and RQ, respiratory quotient. *, significantly different from pre-acclimation value by paired *t* test ($p < 0.05$).

Table 5. Work intensity relative to maximal aerobic power (RWI) and subjective ratings of perceived exertion (RPE) and thermal discomfort (RTD). Untrained (UT) subjects and subjects participating in endurance training (ET) wearing standard combat clothing and NBC protective clothing before and after heat acclimation

Group	Condition	Standard Combat Clothing		
		RWI (%)	RPE	RTD
UT	Pre-acclimation	40.2±1.5	3.0±0.4	8.9±0.3
	Post-acclimation	37.0±1.3*	2.8±0.4	8.1±0.3*
ET	Pre-acclimation	37.2±2.1	2.8±0.5	8.3±0.3
	Post-acclimation	36.9±1.1	2.5±0.4	8.0±0.3*

Group	Condition	NBC Protective Clothing		
		RWI (%)	RPE	RTD
UT	Pre-acclimation	42.1±1.6	3.5±0.3	8.9±0.3
	Post-acclimation	42.0±1.9	3.1±0.4	8.9±0.3
ET	Pre-acclimation	42.7±1.7	3.2±0.3	9.0±0.1
	Post-acclimation	43.4±1.5	3.1±0.3	8.9±0.2

Values are means ± SEM. n = 9 for the UT group and n = 6 for the ET group. *, significantly different from pre-acclimation value by paired *t* test ($p < 0.05$).

Table 6. Sweat data. Untrained (UT) subjects and subjects participating in endurance training (ET) wearing standard combat clothing and NBC protective clothing before and after heat acclimation

Group	Condition	Standard Combat Clothing		
		SP ($kg \cdot h^{-1}$)	SE ($kg \cdot h^{-1}$)	EE (%)
UT	Pre-acclimation	0.79±0.06	0.60±0.04	76.5±1.9
	Post-acclimation	0.78±0.04	0.59±0.03	76.5±2.3
ET	Pre-acclimation	0.81±0.08	0.60±0.04	75.1±2.5
	Post-acclimation	0.87±0.10	0.63±0.05	74.0±2.9

Group	Condition	NBC Protective Clothing		
		SP ($kg \cdot h^{-1}$)	SE ($kg \cdot h^{-1}$)	EE (%)
UT	Pre-acclimation	1.09±0.10	0.29±0.01	28.5±2.3
	Post-acclimation	1.22±0.11*	0.29±0.02	24.7±1.8
ET	Pre-acclimation	1.36±0.22	0.26±0.02	21.5±3.1
	Post-acclimation	1.45±0.23	0.28±0.03	20.5±1.8

Values are means ± SEM. n = 9 for the UT group and n = 6 for the ET group. SP, rate of sweat production; SE, rate of sweat evaporation; and EE, evaporative efficiency. *, significantly different from pre-acclimation value by paired *t* test ($p < 0.05$).

Table 7. Sweat rate, unadjusted and adjusted for rectal temperature (T_{re}) and mean skin temperature ($\bar{T}_{sk}$). Untrained (UT) subjects and subjects participating in endurance training (ET) wearing standard combat clothing and NBC protective clothing before and after heat acclimation

Group	Condition	Standard Combat Clothing			
		SP ($kg \cdot h^{-1}$)	SP_{adj} ($kg \cdot h^{-1}$)	T_{re} (°C)	$\bar{T}_{sk}$ (°C)
UT	Pre-acclimation	0.79±0.06	0.70±0.08	38.1±0.1	36.0±0.1
	Post-acclimation	0.78±0.04	0.86±0.08	37.8±0.1	35.7±0.1
	Δ	-0.01	+0.16	-0.3*	-0.3*
ET	Pre-acclimation	0.81±0.08	0.81±0.10	38.0±0.1	36.0±0.2
	Post-acclimation	0.87±0.10	0.88±0.10	37.9±0.1	35.9±0.2
	Δ	+0.06	+0.07	-0.1	-0.1

Group	Condition	NBC Protective Clothing			
		SP ($kg \cdot h^{-1}$)	SP_{adj} ($kg \cdot h^{-1}$)	T_{re} (°C)	$\bar{T}_{sk}$ (°C)
UT	Pre-acclimation	1.09±0.10	1.08±0.12	37.9±0.1	36.3±0.1
	Post-acclimation	1.22±0.11	1.23±0.12	37.7±0.1	36.2±0.1
	Δ	+0.13*	+0.15	-0.2*	-0.1
ET	Pre-acclimation	1.36±0.22	1.18±0.27	37.9±0.1	36.5±0.1
	Post-acclimation	1.45±0.23	1.63±0.27	37.6±0.1	36.2±0.1
	Δ	+0.09	+0.45	-0.3*	-0.3*

Values are means ± SEM. n = 9 for the UT group and n = 6 for the ET group. SP, unadjusted sweat production and SP_{adj}, sweat production adjusted for the average T_{re} and $\bar{T}_{sk}$ observed during mean exposure time of 112 min (range: 90-120 min) in standard combat clothing and mean exposure time of 44 min (range: 30-50 min) in NBC protective clothing for the UT group and maximal exposure time of 120 min in standard combat clothing and mean exposure time of 45 min (range: 40-55 min) in NBC protective clothing for the ET group. *, significant differences between pre- and post-acclimation by paired *t* test ($p < 0.05$).

Table 8. Energy balance data. Untrained (UT) subjects and subjects participating in endurance training (ET) wearing standard combat clothing and NBC protective clothing before and after heat acclimation

Group	Condition	Standard Combat Clothing							
		S_1	S_2	M	W	E_{res}	C_{res}	E_{sk}	R+C
UT	Pre	213±12	156±25	882±23	41±1	-56±1	7±0	-689±33	52±1
	Post	193±10	126±20	840±19*	41±1	-53±1*	7±0*	-682±25	55±1*
ET	Pre	184±11	126±26	874±27	40±1	-55±2	7±0	-711±43	51±2
	Post	173±10	66±29*	843±25	40±1	-53±2	7±0	-744±46	52±2

Group	Condition	NBC Protective Clothing							
		S_1	S_2	M	W	E_{res}	C_{res}	E_{sk}	R+C
UT	Pre	504±18	524±39	957±32	43±1	-60±2	8±0	-359±16	22±1
	Post	496±13	532±36	963±29	43±1	-61±2	8±0	-359±25	23±1
ET	Pre	500±24	597±24	999±33	42±1	-63±2	8±0	-325±18	20±1
	Post	471±19*	556±32	976±21	42±1	-62±1	8±0	-348±33	23±1*

Values are means ± SEM in $kJ \cdot m^{-2} \cdot h^{-1}$. n = 9 for the UT group and n = 6 for the ET group. S_1 and S_2, rates of heat storage (estimated by the predictive equation and by resolving the heat balance equation, respectively); M, metabolic rate; W, external work rate; E_{res}, rate of evaporative heat loss from the respiratory tract; C_{res}, rate of convective heat gain through the respiratory tract; E_{sk}, rate of evaporative heat loss from the skin through the clothing; and R+C, rate of dry (radiative and convective) heat gain through the clothed skin. *, significantly different from pre-acclimation value by paired *t* test ($p < 0.05$).

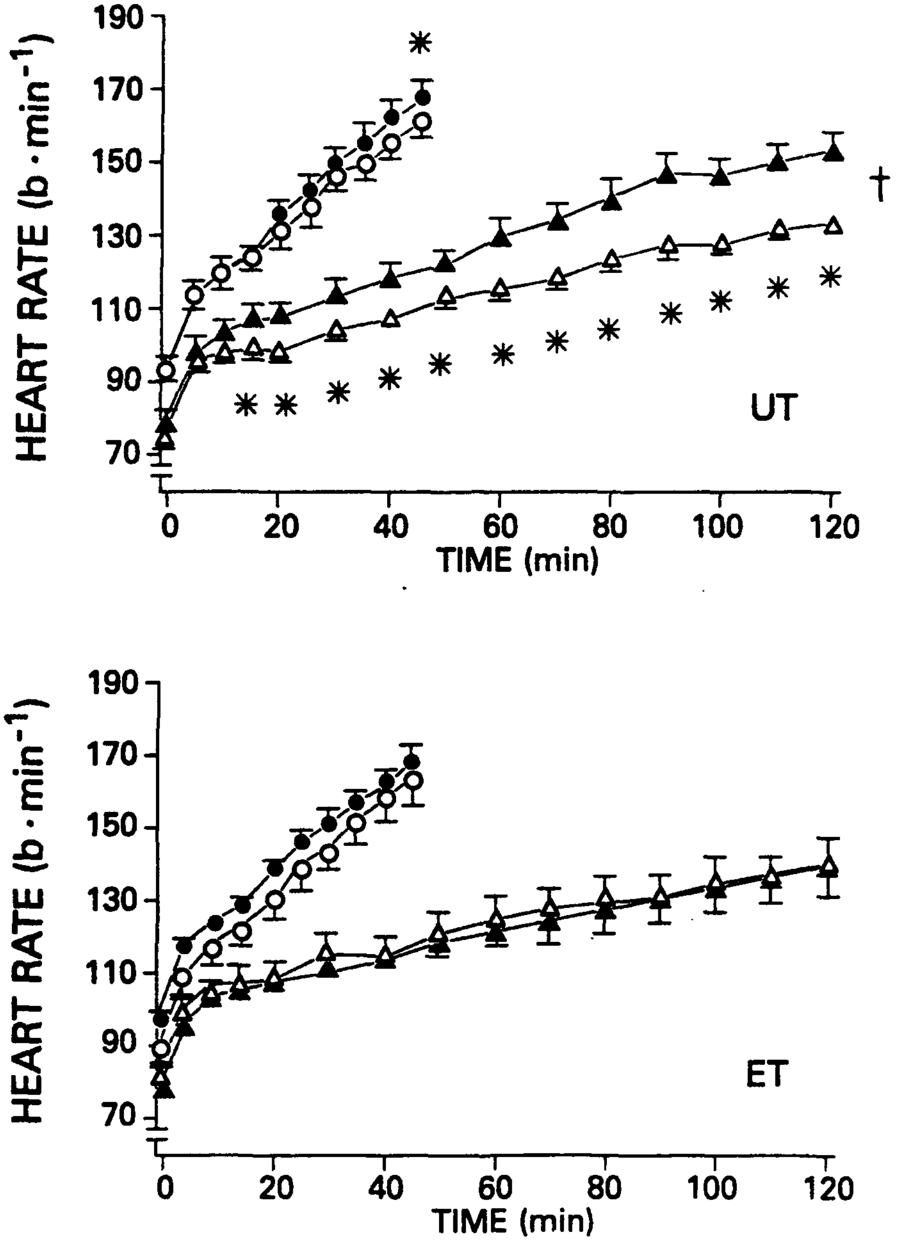


Figure 1. Changes in heart rate during treadmill walking at 40°C. Untrained (UT) and endurance-trained (ET) subjects wearing standard combat clothing (triangles) and NBC protective clothing (circles) before (filled) and after (unfilled) heat acclimation. For the UT group, n = 9 until 90 min; n = 8 at 100 and 110 min; and n = 7 at 120 min for the standard combat clothing trial and n = 9 until 30 min; n = 8 at 35 and 40 min; and n = 7 at 45 min for the NBC protective clothing trial. For the ET group, n = 6 for the standard combat clothing trial and n = 6 until 40 min and n = 5 at 45 min for the NBC protective clothing trial. †, significant differences in mean value pooled over an entire session between pre- and post-acclimation ($p < 0.05$). *, significant differences in the rate of increase in mean value between pre- and post-acclimation ($p < 0.05$).

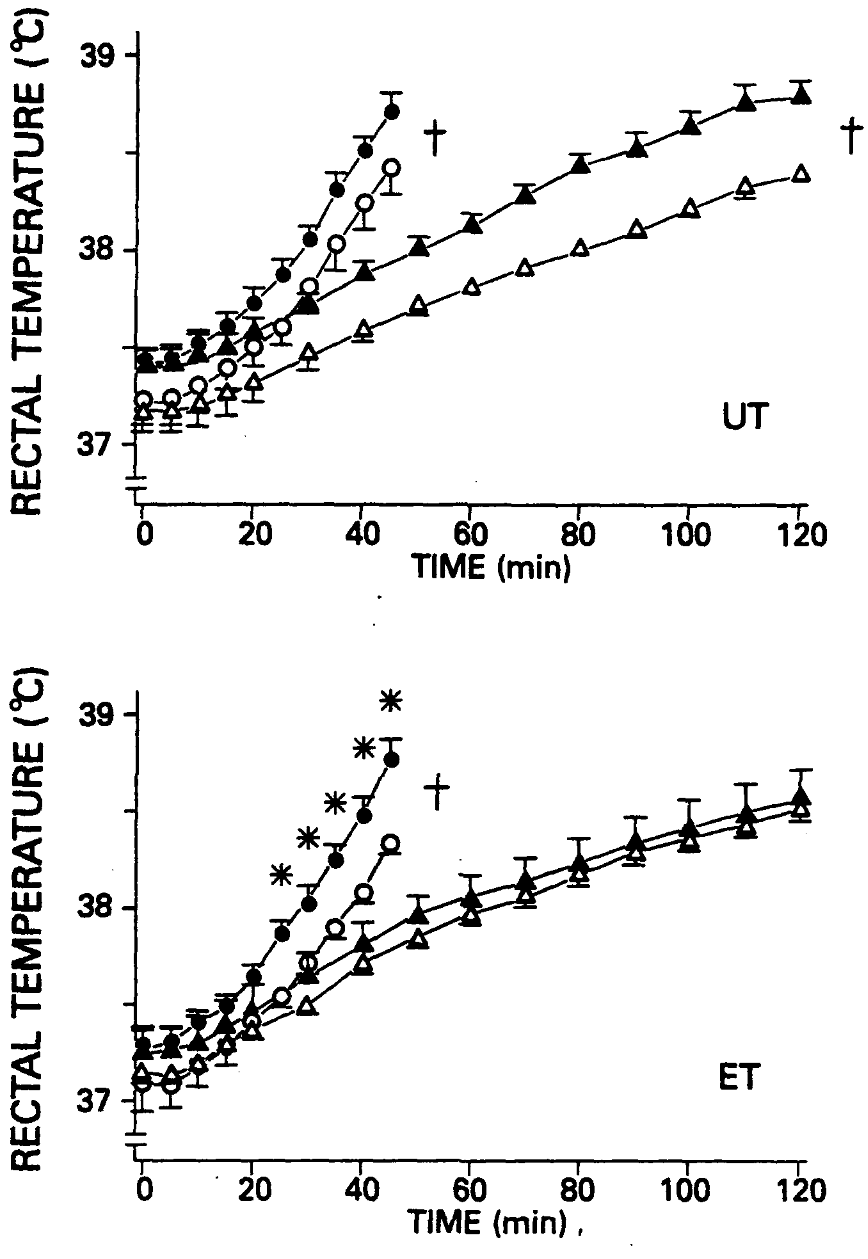
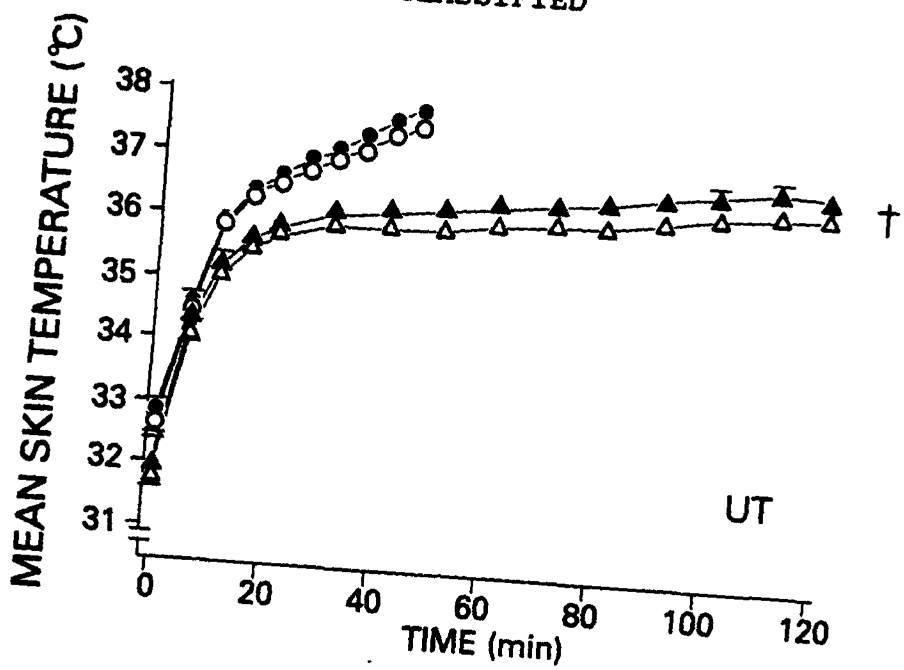


Figure 2. Changes in rectal temperature during treadmill walking at 40°C. Untrained (UT) and endurance-trained (ET) subjects wearing standard combat clothing (triangles) and NBC protective clothing (circles) before (filled) and after (unfilled) heat acclimation. Subject numbers and symbols for statistical differences are as in Figure 1.



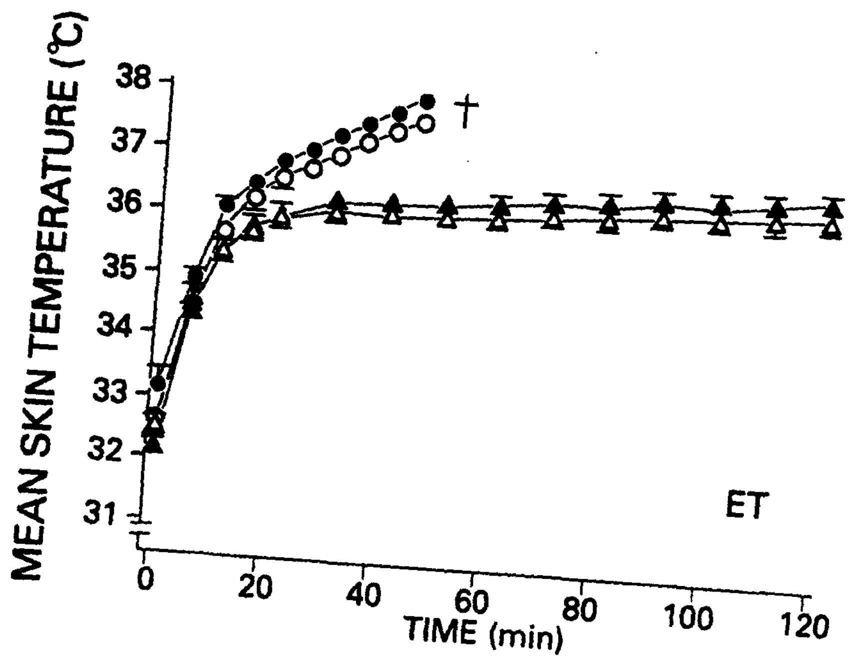


Figure 3. Changes in mean skin temperature during treadmill walking at 40°C. Untrained (UT) and endurance-trained (ET) subjects wearing standard combat clothing (triangles) and NBC protective clothing (circles) before (filled) and after (unfilled) heat acclimation. Subject numbers and symbols for statistical differences are as in Figure 1.

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Research report

5. AUTHOR(S) (Last name, first name, middle initial. If military, show rank, e.g. Doe, Maj. John E.)

Aoyagi Yukitoshi, McLellan Tom M., Shephard Roy J.

6. DOCUMENT DATE (month and year of publication of document)

August, 1993

7a. NO. OF PAGES (total containing information. Include Annexes, Appendices, etc.)

33

7b. NO. OF REFS (total cited in document)

51

8a. PROJECT OR GRANT NO. (if appropriate, the applicable research and development project or grant number under which the document was written. Please specify whether project or grant)

8b. CONTRACT NO. (if appropriate, the applicable number under which the document was written)

University of Toronto contract
W7711-0-7117/01

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Responses were compared between nine untrained (UT) men and six men who had participated in 8 weeks of endurance training (ET). Both groups underwent 6 days of heat acclimation in a climatic chamber that was maintained at 40 ± 0.5°C and 30 ± 1% rh. Subjects were tested before and after acclimation wearing either standard military combat clothing or nuclear, biological and/or chemical (NBC) protective clothing. Test sessions involved treadmill walking at 4.8 $km \cdot h^{-1}$ and 2% grade for a maximum of 120 min. In UT subjects, heat acclimation increased plasma volume (+8 ± 2%), but VO_{2max} and heat-exercise tolerance time were unchanged. When wearing standard combat clothing, acclimation decreased average values of heart rate, rectal temperature (T_{re}), mean skin temperature ($\bar{T}_{sk}$), thermal discomfort, and metabolic heat production. When wearing NBC protective clothing, the only significant change was in T_{re}. Acclimation induced an increase of sweat secretion but no statistically significant increase of sweat evaporation in NBC protective clothing. In ET subjects, acclimation reduced thermal discomfort when wearing standard combat clothing, and T_{re} and $\bar{T}_{sk}$ when wearing NBC protective clothing. The results suggest that heat acclimation did little to improve exercise tolerance when wearing NBC protective clothing in hot environments, although it reduced thermoregulatory strain by lowering mean body temperature, irrespective of training status. Further, acclimation added little to the benefit resulting from participation in 8 weeks of endurance training other than reducing psychological strain when wearing standard combat clothing in hot environments.

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